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NeSOS Based GA Operator for Optimal Single-Phase DG in Unbalanced and Harmonic Polluted Distribution Network

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Abstract: This research discusses the optimization of capacity and locations for multi single-phase distributed generation (DG) in unbalanced distribution systems to reduce power losses, improve bus voltage while maintaining voltage imbalances and harmonics within the acceptable limits. The optimization of single-phase DG uses new enhanced symbiotic organism search (NeSOS) based genetic algorithm (GA) operator. NeSOS is developed by modifying the mutualism and commensalism phases using the random weighted inverse vector. The parasitism phase is modified by introducing sub-phase in parasitism phase. NeSOS based GA operator is validated using the IEEE 33-bus system and tested using an unbalanced 25-bus distribution system. Validation using the IEEE 33-bus distribution system shows that NeSOS based GA operator produces the lowest power loss compared to, chaotic moth-flame optimization (CMFO) based power loss sensitivity factor (PLSF), particle swarm optimization (PSO), improved analytical (IA), loss sensitivity factor (LSF), and hybrid PSO method. Simulations using an unbalanced 25-bus distribution system indicate that NeSOS and SOS successfully reduces active and reactive power loss by 68.24% and 64.93% respectively, however in terms of convergence rate, NeSOS is, on average, 52.39% faster than SOS.

Keywords: GA operator, Harmonic, New enhanced SOS, Random weighted inverse vector, Single-phase, Unbalance.

1. Introduction

The Kyoto Protocol has raised global awareness about environmental concerns [1]. In response, the use of renewable energy sources is increasing and expected to contribute over 30% to the world's electricity supply [2]. The increase in single-phase load and single-phase DG from household sources can result in voltage imbalances, power losses, and equipment damage in the distribution system [3].

In the past twenty years, various studies have explored the advantages of integrating DG into the power system [4, 5]. Those studies generally focused on linear loads, assuming the distribution system is in a balanced state. However, it's crucial to note that the distribution system is fundamentally an unbalanced three-phase system connected to both linear and nonlinear loads [6]. Nonlinear loads in the power system can reach approximately 40-41% of the total load [7]. Harmonics in the distribution system reduced insulation life, increase temperatures and power loss, pressure on insulators, and decrease in power factor [8, 9]. Simplifying an unbalanced system into a balanced system doesn't provide an accurate representation of the actual system.

The impact of load imbalances in the distribution system has been discussed by several researchers. Deterministic methods based on principal component analysis were developed in [10], and an exhaustive search technique in [11]. Optimization of DG based on PSO was carried in [12, 13]. Atom search optimization (ASO) was introduced in [14] and virtual power plant method was developed in [15]. Studies in [11-15] using three-phase DG injection. This scheme is less effective in mitigating voltage imbalance issues.

To address the complex issues in optimizing DG capacity and location, researchers commonly use a combination of sensitivity factors (SF) and artificial intelligence (AI) algorithms. SF is employed to determine the location, while AI is utilized to determine the capacity of DG. For example, loss sensitivity factor (LSF) and improved analytical (IA) method is proposed in [16]. Hybrid analytical method and PSO are developed in [17]. Sujono et al [18] employed sensitivity index and an adaptively modified firefly algorithm (AMFA). LSF and the grasshopper optimization algorithm (GOA) are introduced in [19]. Setyawan et al [20] used LSF to determine the DG location, while DG capacities are optimized using SOS. Power loss sensitivity factor (PLSF) and chaotic moth flame optimization (CMFO) are proposed in [21], while LSF and the golden jackal optimization (GJO) are proposed in [22]. Alzeer and Iqteit [23] employed the LSF and the firefly algorithm (FA). Authors in [18-23] identified DG locations using SF through exhaustive load flow (ELF), which becomes time-consuming in larger distribution systems. To overcome this issue, this research proposed NeSOS based GA operators. This approach incorporated capacities, locations, and phase variables as part of the organisms, allowing simultaneous optimization. The GA operator introduced variability into the location and phase variables for improved results.

The key contributions of this research can be summarized as follows: 1). The utilization of NeSOS in the optimization. NeSOS is a novel algorithm developed from SOS. NeSOS has demonstrated significant performance improvements compared to SOS [24]. 2). Injecting using single-phase DG. Single-phase DG is more effective in addressing voltage imbalances in unbalanced distribution systems compared to three-phase DG. 3). The integration of GA operators, which enables the simultaneous optimization of DG capacities and locations. This eliminates the need for SF, thus accelerating computational time. The rest of this paper is structured as outlined below: Section 2 provides a detailed explanation of NeSOS, and GA operators. Section 3 discusses the validation method, optimization scheme, results, and discussion. Finally, section 4 proposes the research conclusions.

2. Method

2.1 New Enhanced SOS (NeSOS)

NeSOS is an improved version of SOS, developed by Umar et al in 2020 [24]. Enhancements are applied in all phases of SOS algorithm. In the mutualism and commensalism phases, adjustments are made to enhance the exploitation capability of the SOS algorithm by integrating the concept of the random weighted differential vector (RWDV). The $RWDV$ is formulated as follows [24]:

$$RWDV = 0.5 \times [1 - rand(1, D)] \tag{1}$$

The counterpart of RWDV, known as the random weight inverse vector (RWIV) is formulated as:

$$RWIV = 1 - 0.5 \times [1 + rand(1, D)] \tag{2}$$

D represents a dimension. Utilizing Eq. (2), the interaction between organisms X_i and X_j results in new organism as formulated below [24]:

$$X_{i\_N} = X_i + RWIV \times (X_{best} - MV \times BF_1) \tag{3}$$

$$X_{j\_N} = X_j + RWIV \times (X_{best} - MV \times BF_2) \tag{4}$$

i and j are integers $1, 2, 3, \ldots,$ where $i \neq j$. X_{best} is the best organism in the ecosystem. MV is a mutual vector, which is defined as [25]:

$$MV = 0.5(X_i + X_j) \tag{5}$$

BF_1 and BF_2 are benefit factors formulated as [25]:

$$BF_1 = 1 + round(rand(0,1)) \tag{6}$$

$$BF_2 = 1 + round(rand(0,1)) \tag{7}$$

Using $RWIV$ from Eq. (2), the new organism in the commensalism phase is expressed as follows [24]:

$$X_{i\_N} = X_i + RWIV \times (X_{best} - X_j) \tag{8}$$

To reduce excessive organism exploration in the parasitism phase, modifications are made by dividing the parasitism phase into two stages: original parasitism (OP) and random weight parasitism (RWP). RWP is a form of parasitism that includes random weights (RW) from the crow search algorithm.

$$RW = rand(0,1) \times rand(-2,2) \tag{9}$$

Integrating Eq. (9), the random weight parasitic vector (RWPV) is formulated as follows [24]:

$$RWPV = X_i + RW \times (X_{best} - X_j) \tag{10}$$

Eq. (10) is employed in the parasitism phase to enhance the exploitation capability of the NeSOS algorithm. Fig. 1 illustrates the NeSOS algorithm flowchart.

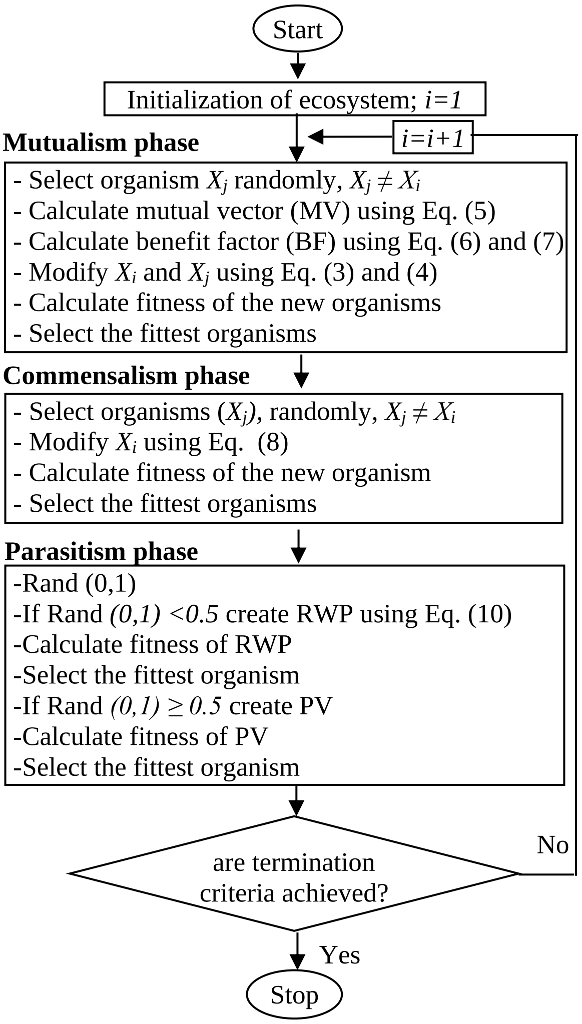

Figure. 1 NeSOS Flowchart

2.2 GA operator

The typical method for identifying the optimal location and capacity of DG using artificial intelligence (AI) involves separate optimization, as indicated in [16-23]. The determination of location relies on SF, while capacity is determined through the utilization of AI. The SF values are derived through a recurring load flow procedure demanding a substantial investment of both time and energy. The integration of location and phase variables into the optimization process is intended to be addressed by employing NeSOS with a GA operator. The GA operator is used to introduce variability to the location and phase variables of organisms in NeSOS. Simultaneously optimizing the location and capacity of DG can reduce computational time. In simultaneous capacity and location optimization schemes for DG, each organism is represented by four variables: location (L), phase (P), and capacity (C). The location variable contains random numbers representing bus numbers. The phase variable consists of integers 1-3 representing phases R, S, and T. Meanwhile, the DG capacity variable is represented by random numbers between 0-1, where 0 and 1 represent the minimum and maximum DG capacities. If m is the number of DG units, then an organism in the algorithm can be described as follows:

$$X = [L_1, L_2,.. L_m; P_1, P_2,.. P_m; C_1, C_2,.. C_m;] \quad (11)$$

$L_1, L_2, ...L_m$ represent the locations of DG. $P_1, P_2, ...P_m$ are the locations of DG, while $C_1, C_2, ...C_m$ represent the capacities of DG. A GA operator is applied in the mutualism and parasitism phases to generate variations in organisms for phase and location variables. During the mutualism phase, interactions between two organisms result in new organisms that include DG capacities, locations, and phases. Changes in DG capacities follow a process like how an SOS typically operates, while for location and phase variables, a one-point simple crossover is used. To explore potential solutions related to location and phase variables, a mutation process is employed during the parasitism phase.

3. Results and discussion

3.1 NeSOS based GA operator validation

To demonstrate the effectiveness of this method, DG optimization is conducted on the IEEE 33-bus distribution system to minimize active power loss. NeSOS is then compared with several methods from references, such as IA, LSF, [16], PSO, hybrid PSO [17], CMFO [21] and SOS. The IEEE 33-bus system data is adopted from [16]. The parameter settings for the NeSOS and SOS based GA operator are as follows: the number of ecosystems = 20, number of iterations = 100 and maximum number of fitness evaluations (NFE) = 300, crossover probability = 0.95, mutation probability = 0.05. The parameter settings for IA, and LSF follow [16]; PSO and hybrid PSO follow [17], while CMFO follow [21]. The optimization scheme consists of two scenarios, namely using 2 DGs and 3 DGs. The optimization results are presented in Table 1. Bolded numbers represent the best value.

The optimization results presented in Table 1 demonstrate that in the 2 DG scheme, the NeSOS and SOS based GA operator methods exhibit the lowest power losses at 87.16 kW, surpassing CMFO, PSO, Hybrid, IA, and SF method. Notably, NeSOS and SOS effectively reduce power losses by 58.69%.

Tabel 1. Optimal capacity and location of DG on IEEE 33 bus distribution system

Scheme	Method	Location	Sise (MW)	Capacity (MW)	Loss (kW)	Iteration
No DG	-	-	-	-	211.000	-
2 DG	IA [16]	6 14	1.800 0.720	2.520	91.630	NA
	LSF [16]	18 33	0.720 0.900	1.620	100.690	NA
	PSO [17]	13 30	0.850 1.160	2.010	87.170	NA
	Hybrid [17]	13 30	0.830 1.110	1.940	87.280	NA
	PLSF+CMFO [21]	13 30	0.8515 1.1576	2.009	87.166	NA
	SOS+GA operator	13 30	0.852 1.158	2.010	**87.160**	10
	NeSOS+GA operator	13 30	0.852 1.158	2.010	**87.160**	**6**
3 DG	IA [16]	6 12 31	0.900 0.900 0.720	2.520	81.050	NA
	LSF [16]	18 25 33	0.810 0.720 0.900	2.430	85.070	NA
	PSO [17]	13 24 30	0.770 1.090 1.070	2.930	72.790	NA
	Hybrid [17]	13 24 30	0.790 1.070 1.010	2.870	72.890	NA
	PLSF +CMFO [21]	13 24 30	0.8017 1.0913 1.0537	2.947	72.786	NA
	SOS+GA operator	13 24 30	0.802 1.091 1.053	2.946	**72.781**	22
	NeSOS+GA operator	13 24 30	0.802 1.091 1.053	2.946	**72.781**	**14**

NA=not available

In the optimization scenario involving 3 DG, NeSOS and SOS consistently achieve the lowest power losses, even with slightly higher DG injections. The power losses reduction by NeSOS and SOS in this scenario amounts to 65.51%, outperforming CMFO, PSO, Hybrid, IA, and SF. The optimization results reveal that the CMFO-based PLSF method achieves the second lowest active power loss. This method fundamentally involves two distinct steps: identifying DG locations through PLSF and determining DG capacity using CMFO. Optimizing DG capacity and location separately requires more time compared to simultaneous optimization. Analytical methods like SF and IA essentially employ an approach through the linearization of nonlinear equations. The limitations within this method lead to suboptimal results.

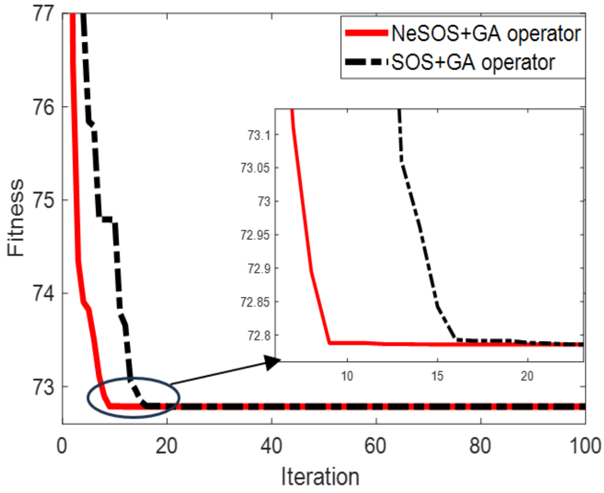

Figure. 2 NeSOS and SOS based GA operator curve convergence for 3 DG optimization scheme

Hybrid methods integrate the loss formula approach with PSO, where PSO determines the location, and the loss formula determines the DG capacity. While PSO accurately identifies the DG location in this scheme, the loss formula method falls short of precisely determining the DG capacity. The hybrid method exhibits performance below that of the NeSOS and CMFO method.

In terms of convergence rate, on average, the NeSOS-based GA operator in this scheme is 38.18% faster compared to the SOS-based GA operator. The convergence curves for NeSOS and SOS based GA operator are illustrated in Fig. 2.

3.2 NeSOS based GA operator for optimal single-phase DG

The objective of this research is to reduce power loss, maintain bus voltages, and ensure that voltage imbalances and harmonics are within acceptable limits. Therefore, this study is a multi-objective research.

3.2.1 Objectives

The objective of this study is to reduce power losses, maintain bus voltages, and ensure that voltage imbalances are within acceptable limits. Reducing power loss in the distribution systems serves not only for the efficiency of electrical energy but also for economic reasons. The objective function related to active power loss can be written as follows:

$$F_1 = \left(\frac{PL_{DG}}{PL_o}\right) \tag{12}$$

PLo and *PL*$_{DG}$ are active power loss before and after DG installation respectively.

To ensure the quality and reliability of the electric power system, it is standard practice to keep voltage levels within a range of *1±5%* per unit. The objective function associated with bus voltage can be expressed as follows:

$$F_2 = \prod_{i=1}^{nbus} VVR_i \tag{13}$$

VVR_i is the bus voltage violation rate for bus i, expressed as follows:

$$VVR_i = \begin{cases} 1 \quad \text{if} \quad 0.95 \leq V_i \leq 1.05 \\ exp(\mu|1 - V_i|)\,, \text{for other } V_i \end{cases} \tag{14}$$

V_i is voltage at bus i. μ is weight factor.

Voltage imbalance is assessed by various standards, including those established by the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE). In IEC standards, voltage imbalance is denoted as the voltage unbalance factor (VUF), representing the ratio of negative to positive sequence phase voltages [3]. Meanwhile, according to IEEE, voltage imbalance is referred to as the phase voltage unbalance ratio (PVUR). PVUR is expressed as follows [3]:

$$PVUR = \max\left(\left|V_A - V_{avg}^P\right|, \left|V_B - V_{avg}^P\right| \left|V_C - V_{avg}^P\right|\right) \times \frac{100\%}{V_{avg}^P} \tag{15}$$

V_A, V_B, V_C, are phase voltages, while V^P_{avg} is phase average voltage. Voltage unbalance in this study is evaluated using PVUR because for voltage imbalances below 5%, the difference between PVUR and VUR is not significant. Based on the IEEE 141-1993 standard, PVUR should not exceed 2% [3]. The objective function related to PVUR is formulated as follows:

$$F_3 = \prod_{i=1}^{nbus} VUVR_i \tag{16}$$

$VUVR_i$ is the voltage unbalance violation rate for bus *i*, which is defined as follows:

$$VVR_i = \begin{cases} 1 \quad \text{if} \quad PVUR_i \leq 2 \\ exp\left(\frac{PVUR_i}{2}\right)^{0.8}, \text{for other } PVUR_i \end{cases} \tag{17}$$

$PVUR_i$ and $VUVR_i$ are phase voltage unbalance and voltage unbalance violation rate for bus i.

Based on the IEEE-519 standard, the individual harmonic distortion (iHD) and total harmonic distortion (THD) must not exceed 3% and 5%, respectively [7, 27]. The individual and total harmonic violations are formulated as follows:

$$IHVR_i = \begin{cases} 1 \;\; if \;\; iHD_i \leq 3 \\ exp\left(\frac{iHD_i}{3}\right)^{0.8}, if \;\; iHD_i > 3 \end{cases} \tag{18}$$

$$THVR_i = \begin{cases} 1 \;\; if \;\; THD_i \leq 5 \\ exp\left(\frac{THD_i}{5}\right)^{0.8}, if \;\; THD_i > 5 \end{cases} \tag{19}$$

$IHVR_i$ and $THVR_i$ denote the rates of individual and total harmonic violations at bus i, while THD_i and iHD_i signify the total and individual harmonic distortions at bus i. The objective function associated with harmonics can be calculated as follows:

$$F_4 = \prod_{i=1}^{nbus} IHVRi \times \prod_{i=1}^{nbus} THVRi \tag{20}$$

The objective function in this research is formulated:

$$F = min\,(\mu_1 F_1 + \mu_2 F_2 + \mu_3 F_3 + \mu_4 F_4) \tag{21}$$

μ_1, μ_2, μ_3, and μ_4 are weight factors.

3.2.2 Constrains

The objective function in Eq. (21) must adhere to several constraints, including power balance, bus voltage, harmonic content, DG size, and penetration level. The power balance in the optimization can be expressed as the following equation:

$$P_{Gi} + P_{DGi} + P_{Di} = \sum_{i=1}^{n} V_i V_j (G_{ij} Cos(\theta_i - \theta_j) + B_{ij} Sin(\theta_i - \theta_j)) \tag{22}$$

$$Q_{Gi} + Q_{DGi} + Q_{Di} = \sum_{i=1}^{n} V_i V_j (G_{ij} Sin(\theta_i - \theta_j) + B_{ij} Cos(\theta_i - \theta_j)) \tag{23}$$

P_{Gi}, P_{DGi}, P_{Di} are represent the active power of the generator, DG, and load, while Q_{Gi}, Q_{DGi}, Q_{Di} represent the reactive power of the generator, DG, and load. The voltage at each bus (V_i) must satisfy the following requirements:

$$0.95\, pu \leq V_i \leq 1.05\, pu \tag{24}$$

Based on the IEEE-519 standard, the THD and iHD on the network should adhere to the specific limits as formulated below:

Table 2. Load data of 25 bus test system

No Bus	S_A (kVA)	S_B (kVA)	S_C (kVA)	No Bus	S_A (kVA)	S_B (kVA)	S_C (kVA)
1	0.0	0.0	0.0	14	50.0 + j35.0	50.0 + j40.0	60.0 + j45.0
2	0.0	0.0	0.0	15	133.3+j100	133.3 + j100	133.3 + j100
3	35.0 + j25.0	40.0 + j30.0	45.0 + j32.0	16	40.0 + j30.0	40.0 + j30.0	40.0 + j30.0
4	50.0 + j40.0	60.0+j45.0	50.0 + j35.0	17	40.0 + j30.0	35.0 + j25.0	45.0 + j32.0
5	40.0 + j30.0	40.0 + j30.0	40.0 + j30.0	18	40.0 + j30.0	40.0 + j30.0	40.0 + j30.0
6	40.0 + j30.0	45.0 + j32.0	35.0 + j25.0	19	35.0 + j25.0	40.0 + j30.0	45.0 + j32.0
7	0.0	0.0	0.0	20	60.0 + j45.0	50.0 + j35.0	50.0 + j40.0
8	40.0 + j30.0	40.0 + j30.0	40.0 + j30.0	21	40.0 + j30.0	35.0 + j25.0	45.0 + j32.0
9	60.0 + j45.0	50.0 + j40.0	50.0 + j35.0	22	50.0 + j35.0	60.0 + j45.0	50.0 + j40.0
10	35.0 + j25.0	40.0 + j30.0	45.0 + j32.0	23	60.0 + j45.0	50.0 + j40.0	50.0 + j35.0
11	45.0 + j32.0	35.0 + j25.0	40.0 + j30.0	24	35.0 + j25.0	45.0 + j32.0	40.0 + j30.0
12	250.0 + j35.0	60.0 + j45.0	50.0 + j40.0	25	60.0 + j25.0	50.0 + j30.0	50.0 + j35.0
13	135.0+ j25.0	45.0 + j32.0	40.0 + j30.0				

$$THD(\%) \leq 5\% \tag{25}$$

$$iHD(\%) \leq 3\% \tag{26}$$

The injection of DG into the distribution system must meet certain capacity requirements as follows:

$$P_{DGmin} \leq P_{DG} \leq P_{DGmax} \tag{27}$$

$$Q_{DGmin} \leq Q_{DG} \leq Q_{DGmax} \tag{28}$$

P_{DGmin}, P_{DGmax} are minimum and maximum active power of DG, while Q_{DGmin}, Q_{DGmax} are minimum and maximum reactive power of DG.

To preserve the power system's quality, it is essential to control the total power introduced by DG at a specific level. The penetration level (α) signifies the proportion of DG-injected power to the overall load within the system.

$$\alpha = \frac{Total\ DG\ Injection}{Total\ Load} \tag{29}$$

3.2.3 Data test system and optimization scheme

The NeSOS system's performance will be evaluated using a 25-bus test system. In line with the goals of this paper, certain adjustments have been applied to the load data. This 25-bus test system is composed of 24 branches and 25 nodes, with a total load of 3.5399 MW and 2.393 MVar. Harmonic sources are presumed to be associated with buses 12, 15, 19, 22, and 25. Load data can be found in Table 2, line data is provided in [28] and harmonic injection data is provided in [29].

The simultaneous optimization of DG location and capacity is performed using the NeSOS based GA operator. The total number of single-phase DG units used is 9, consisting of 2 types: those supplying active power (Type I) and those supplying reactive power (Type II). Each DG has a maximum capacity of 250 kW and 250 kVar for DG type I and type II respectively. It is assumed that these DGs do not introduce harmonic disturbances. The NeSOS based GA operator is configured with specific parameters: ecosystems=20, and maximum iteration=150 (maximum NFE=450). Crossover and mutation probability are 0.95, and 0.05 respectively.

The optimization performed consists of three schemes, namely optimization using DG type I, using DG type II, and multi-type of scheme. To demonstrate the effectiveness of NeSOS in solving optimization problems, simulations were also conducted using the SOS based GA operator. In the multi-type of simulation scheme, optimization is also carried out using a three-phase DG.

3.2.4 Initial condition

The initial load flow indicates that most of bus voltages are below 0.95 per unit (pu). The lowest voltage recorded at 0.8942 pu on bus 12a. The PVUR for buses 10-13 exceeds the IEEE 141 standard, with a maximum PVUR of 2.8586% observed at bus 12. THD on buses 9-13, specifically in phase a, exceeds 5%. The highest THD recorded is 6.974%, found at bus 12a. iHD for all orders are below 3%. The active and reactive power losses are 195.288 kW and 261.496 kVar respectively.

3.2.5 Optimization of single-phase DG type I

The optimization results for 9 single-phase DG units of type I on a 25-bus system indicate that the most suitable locations for installing single-phase DG units are at buses 11c, 12a, 12b, 13a, 14b, 15a, 15c,

Table 3. The optimization results for DG Type I

Description	SOS	NeSOS
Location (Bus)	11c, 12a,12b 13a, 14b,15a 15c, 18c, 23b	11c,12a, 12b 13a,14b,15a 15c,18c, 23b
Capacity (MVA)	0.25, 0.25, 0.25 0.25, 0.25, 0.25 0.25, 0.25, 0.25	0.25, 0.25, 0.25 0.25, 0.25, 0.25 0.25, 0.25, 0.25
P loss (kW)	70.77	70.77
Q loss (kW)	99.36	99.36
Min. voltage	0.958	0.958
Max. PVUR	0.73	0.73
Max. THD	2.40	2.40
Iteration	83.00	32.00

18c, and 23b. Each DG unit has a capacity of 0.25 MW. This optimization leads to a 63.76% reduction in active power loss and a 62.00% reduction in reactive power loss. Furthermore, it enhances bus voltages and improves PVUR and THD. The lowest bus voltage is 0.958 pu, and the maximum PVUR and THD are reduced by 74.48% and 65.57%, respectively, ensuring compliance with the allowed PVUR and THD limits. The results of the optimization process for 9 single-phase DG units of type I on the 25-bus system using NeSOS are identical to those obtained through the SOS algorithm. The only difference lies in the convergence speed of each algorithm. NeSOS based GA operator converges 61.45% faster than SOS based GA operator. The optimization results for DG Type I are shown in Table 3.

3.2.6 Optimization of single-phase DG type II

The optimization outcomes for 9 single-phase DG units of type II indicate that the best positions and sizes for these units are as follows: 0.25 MVar at buses 9b, 12c, 13c, 17b, and 25a; 0.46 MVar at bus 11a; 0.23 MVar at bus 15a; and 0.18 MVar at bus 18a. The inclusion of these 9 single-phase DG units results in a reduction of active and reactive power losses by 14.90% and 19.37%, respectively. The lowest bus voltage is 0.952 pu, and the maximum PVUR and THD are 1.575% and 5.00%, respectively. The optimization results for the 9 single-phase DG units of type II on the 25-bus system using the NeSOS algorithm are the same as those obtained using the SOS algorithms. The difference lies in the speed of convergence for each algorithm. NeSOS converges at the 44th iteration, while SOS converges at the 74th iteration. NeSOS achieves convergence 40.54% faster than SOS The optimization results are shown in Table 4.

Table 4. The optimization results for DG Type II

Description	SOS	NeSOS
Location (Bus)	9b, 11a, 11a 12c, 13c, 15a 16a, 17b, 25a	9b, 11a, 11a 12c, 13c, 15a 16a, 17b, 25a
Capacity (MVar)	0.25 0.25 0.21 0.25 0.25 0.23 0.18 0.25 0.25	0.25 0.25 0.21 0.25 0.25 0.23 0.18 0.25 0.25
P loss (kW)	166.199	166.199
Q loss (kW)	210.849	210.849
Min. voltage (pu)	0.952	0.952
Max. PVUR (%)	1.57	1.57
Max. THD (%)	5.00	5.00
Iteration	74	44

3.2.7 Optimization of multi-type single-phase DG

This approach simultaneously utilizes DG units of type I and type II. The optimization findings reveal that the most efficient placement and sizing for nine DG units are 0.25 MVar each at buses 10c, 11a, and 11b, as well as 0.25 MW each at buses 11b, 11c, 12a, 10c, 11a, and bus 11b. This optimization successfully reduces power losses, enhances bus voltages, and improves both PVUR and THD values. Active and reactive power losses are diminished by 68.24% and 64.93%, respectively. The maximum PVUR and THD are reduced by 72.71% and 62.23%, respectively. Minimum bus voltages, maximum PVUR, and THD are within acceptable limits. The optimization results for 9 single-phase DG units of types I and II in a 25-bus system using NeSOS are in line with the results obtained using SOS, with the primary distinction being the convergence rate of each algorithm. NeSOS converges 55.17% faster compared to SOS. Convergence characteristics for NeSOS and SOS are depicted in Fig. 3, while the optimization results are presented in Table 5.

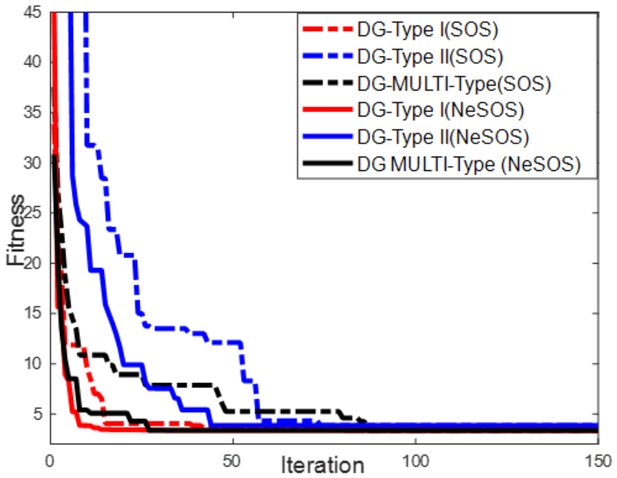

Figure. 3 Convergence curve

Table 5. Optimal location and capacity of single-phase and three phase DG

Scheme	Location (Bus)	Capacity	Voltage (pu)		Ploss (kW)	Loss reduction (%)	PVUR(%)		THD(%)	
			Min	Mean			Max	Mean	Max	Mean
No DG	-	-	0.894	0.948	195.290	-	2.86	0.41	6.97	2.32
9 DG 1ϕ	10c 11a 11b 11b 11c 12a 10c 11a 11b	3 x 0.25 MVar 3 x 0.25 MW 3 x 0.25 MW	0.960	0.973	62.030	68.24	0.78	0.224	2.284	1.251
3 DG 3ϕ	11 15 12	2 x 0.75 MW 1 x 0.75 MVar	0.956	0.974	100.171	48.71	1.99	0.772	3.484	1.471

Table 5 shows that the optimization of 9 single-phase DGs outperforms using 3 three phase DGs with the same capacity across all parameters. Concerning bus voltages, the single-phase DGs results in a higher minimum bus voltage compared to the three phase DG scheme. The reduction in active power loss achieved by the single-phase DG scheme is 68.24%, significantly surpassing the 48.71% reduction in the three-phase DG scheme. Regarding its performance in mitigating voltage imbalance, the single-phase DG scheme exhibits an average PVUR of 0.224%, notably lower than the three phase DG scheme. The single-phase DG performs better in reducing THD with a maximum THD of 2.284%, whereas the three phase DG scheme has maximum THD of 3.484%. These findings suggest that introducing single-phase DG into an unbalanced distribution system yields superior performance compared to the three phase DG scheme.

4. Conclusions

This research explores the implementation of the NeSOS based GA operator to optimize the location and capacity of single-phase DGs in unbalanced distribution systems. Validation using the IEEE 33-bus distribution system demonstrates that the NeSOS based GA operator outperforms CMFO based PLSF, PSO, Hybrid, IA, and SF methods, yielding the lowest power losses. The method achieves reductions of 58.69% and 65.51% in power losses for the 2 DG and 3 DG schemes, respectively. Simulation results using an unbalanced 25-bus distribution system indicate that the simultaneous installation of DGs of type I and type II proves to be the most effective strategy in minimizing power losses. This approach significantly reduces both active and reactive power losses by 68.24% and 64.93%, respectively. In terms of convergence speed, NeSOS is, on average, 52.39% faster than SOS.

Conflicts of Interest

The authors declare no conflict of interest regarding this research or its funding.

Author Contributions

Umar contributed to collecting data, data analysis, algorithm development and implementation, simulations, and paper completion.

Notations

$RWDV$	random weighted differential vector
$rand$	random number
D	dimensions
$X_i,\ X_j$	organism i and j
X_{best}	the best organisms in the ecosystem
MV	mutual vector
BF	benefit factor
$X_{i\_N},\ X_{i\_N}$	new organism
RW	random weight
$RWPV$	random weight parasitic vector
X	organisms for DG optimization
$L_1, L_2, ..L_m$	string locations for DG optimization
$P_1, P_2, ..P_m$	string phases for DG optimization
$C_1, C_2, ..C_m$	string capacities for DG optimization
PL_{DG}	active power loss after DG placement
PL_o	active power loss before DG placement
V_i	voltage at bus i
VVR_i	voltage violation rate for bus i
μ	weight factor
$PVUR$	phase voltage unbalance ratio
$V_A\ ,V_B\ ,V_C$	phase voltages
V_{avg}^P	phase average voltage
$VUVR$	voltage unbalance violation rate
iHD_i	individual harmonic at bus i
THD_i	total harmonic distortion at bus i
$IHVR$	individual harmonic violation rate
$THVR$	total harmonic violation rate
P_{Gi}	active power of generator i
P_{DGi}	active power of DG i
P_{Di}	active power of load i
G_{ij}	conductance between bus i and bus j
B_{ij}	susceptance between bus i and bus j
P_{DGmin}	minimum active power of DG
P_{DGmax}	maximum active power of DG
Q_{DGmin}	minimum reactive power of DG
Q_{DGmax}	maximum reactive power of DG
α	total penetration level of DG

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